Renormalization of BSM theories

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Why being an optimist?

- 10 years to develop a tool
- BSM predictions needed for discovery (and for limit setting?)
- Experience with one model can be used for others

Need for both, optimists and pessimists

Renormalization

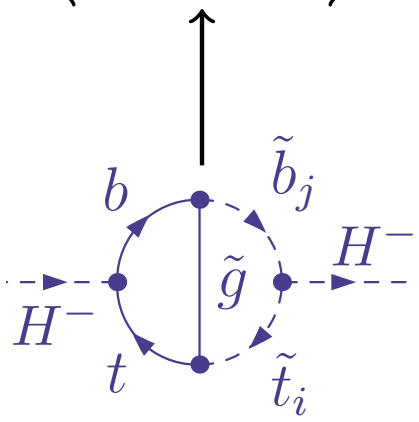
Choice of a renormalization scheme

(including set of independent input parameters)

$\Rightarrow$ Establish meaning of parameters

At higher orders:

Physical observables $\xleftrightarrow{\text{quantum corrections}}$ Parameters



Different aspects

Regularization scheme

Symmetry relations
$\rightarrow$ relations between masses

Gauge independence

Additional parameters

Purpose

Numerical stability:
- Good expansion points
- Parameter scans

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Choice of the regularization scheme

- Preferably symmetry conserving (see e.g. Gnendinger et al, arXiv:1705.01827])

  $\rightarrow$ otherwise symmetry-restoring counterterms might be needed

Example: SUSY theories:

Dimensional regularization breaks SUSY

$\rightarrow$ Add SUSY-restoring counterterms

$\rightarrow$ Use dimensional reduction:

- some SUSY relations explicitly checked at 1- and 2-loop level

(see e.g [Capper, Jones, van Nieuvenhuizen 80; Hollik, Stöckinger, hep-ph/0509298])

Choice of the regularization scheme

In the following:

Assumption:

Symmetry-conserving regularization schemes are applied

$\Rightarrow$ Multiplicative renormalization possible:

Parameters: $g \to Z_g g$

Fields: $\phi \to Z_\phi^{\frac{1}{2}} \phi$

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Input parameter

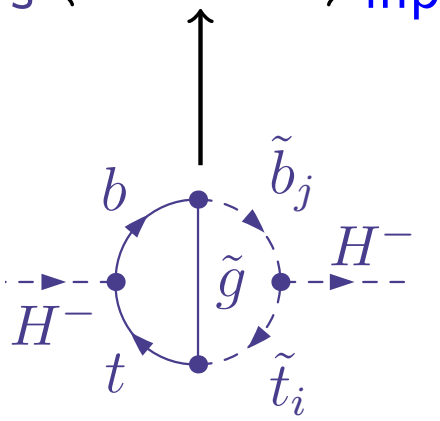
General procedure:

- Identify the fundamental parameters of the Lagrangian
- fundamental parameters $\xrightarrow{\text{replace}}$ chosen input parameters

Important: Careful bookkeeping needed

Of course:

fundamental parameters $\xleftrightarrow{\text{quantum corrections}}$ input parameters



Symmetries

Symmetries can reduce the number of fundamental parameters

Example: SUSY theories:

One generation of squarks in the MSSM:

Soft-SUSY-breaking Lagrangian:

$$\mathcal{L}_{\text{soft}} = M_L \tilde{Q}_L^\dagger \tilde{Q}_L + M_{R_{\tilde{u}}} \tilde{u}_R^\dagger \tilde{u}_R + M_{R_{\tilde{d}}} \tilde{d}_R^\dagger \tilde{d}_R + \ldots \quad \text{with} \quad \tilde{Q}_L = \begin{pmatrix} \tilde{u}_L \\ \tilde{d}_L \end{pmatrix}$$

$\Rightarrow$ 4 particles
3 mass parameters due to $SU(2)$ symmetry

$\Rightarrow$ only three masses can be chosen independently,
one mass depends on the other three masses

Mass relations

Mass^2 as dependent parameter (not an input), here $m^2_{\tilde{d}_1}$:

(see e.g. [Heinemeyer, H.R., Schappacher, 1007.0689])

- Squarks only internal particles: Procedure okay (with only 3 on-shell masses)
  (in the loop)

Problem: Thresholds are shifted

Mass relations

- Squarks also external particles (external $\hat{=}$ on-shell):
  - ▷ use one-loop on-shell masses for external particles:

$$m_{\tilde{d}_1}^{\text{os}^2} = m_{\tilde{d}_1}^{\text{tree}^2} + \delta^{\text{dep.}} m_{\tilde{d}_1}^2 - \Sigma_{\tilde{d}_1\tilde{d}_1}(m_{\tilde{d}_1}^2)$$

$\uparrow$

dependent on
other counterterms

$\Rightarrow$ Problems with IR divergences cancellation
(loops: $m_{\tilde{b}_1}^{\text{tree}^2}$, external: $m_{\tilde{d}_1}^{\text{os}^2}$)

  - ▷ define also $m_{\tilde{d}_1}^2$ as on-shell (further renormalization condition):

$\Rightarrow$ Symmetries have to be restored (here: use $M_{L_{\tilde{u}}}^{2,1-\text{loop}} = M_{L_{\tilde{d}}}^{2,1-\text{loop}}$)

$\Rightarrow$ Loop-corrected masses (also [Bartl, Eberl, Hidaka, Kraml, Majerotto, Porod, Yamada, hep-ph/9806299; Brignole, Degrassi, Slavich, Zwirner, hep-ph/0112177])

$\Rightarrow$ Possible: Problems with UV/IR divergences cancellation

Mass relations

Further problem:

If $m_{\tilde{d}_1}$ not input,

then $\tilde{d}_1 \to \tilde{d}_L$ for no mixing

Often: Mass ordering chosen:

$$m_{\tilde{d}_1} \leq m_{\tilde{d}_2}$$

No problem if $m_{\tilde{d}_L} \leq m_{\tilde{d}_R}$

Otherwise: 2 possibilities to avoid unphysical divergences

- change renormalization prescription:

  $$m_{\tilde{d}_1}, m_{\tilde{d}_2} \to m_{\tilde{d}_1}, m_{\tilde{d}_2}$$

  [Hollik, H.R., hep-ph/0305328]

- change mass ordering

Mass relations

Other examples:

- Charginos/Neutralinos (MSSM): 2 independent masses
  [Fritzsche, Hollik, hep-ph/0203159; Baro, Boudjema, 0807.4668;
  Chatterjee, Drees, Kulkarni, Xu, 1107.5218;
  Fritzsche, Heinemeyer, H.R., Schappacher, 1111.7289;
  Bharucha, Fowler, Moortgat-Pick, Weiglein, 1211.3134]

- Higgs-bosons in the MSSM: 1 independent mass

  $\Rightarrow$ SM-like Higgs-boson mass constrains parameter space
  [Chankowski, Pokorski, Rosiek, hep-ph/9303309; Dabelstein, hep-ph/9409375;
  Baro, Boudjema, Semenov, 0807.4668;
  Frank, Hahn, Heinemeyer, Hollik, H.R., Weiglein, hep-ph/0611326]

- Higgs-bosons in the NMSSM (and Charginos/Neutralinos)
  [Ender, Graf, Mühlleitner, H.R., 1111.4952;
  Graf, Gröber, Mühlleitner, H. R., Walz, 1206.6806;
  Drechsel, Galeta, Heinemeyer, Weiglein, 1601.08100;
  Bélanger, Bizouard, Boudjema, Chalons, 1602.05495; 1705.02209]

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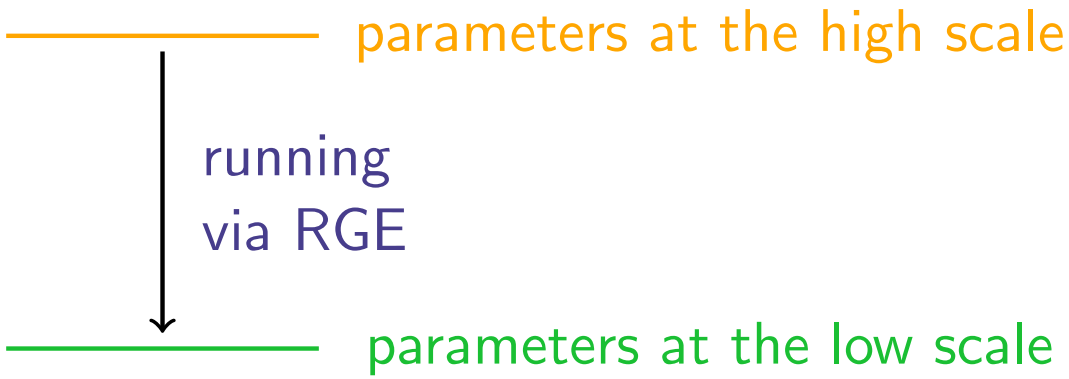
Purpose and additional parameters

In BSM models: Additional parameters e.g. couplings

Possible renormalization conditions:

- High-scale scenario $\rightarrow$ effects at low scale:



Useful choice: Running parameters ($\overline{\text{MS}}$, $\overline{\text{DR}}$ scheme)

Otherwise: conversion of parameters

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- Easily applying experimental constraints e.g. on masses:

  Choose as many masses on-shell as possible

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- Further parameters?
  - $\star$ $\overline{\text{MS}}/\overline{\text{DR}}$ scheme?
  - $\star$ Via full processes?
  - $\star$ Via vertices?

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- What about mixing angles?

Mixing angles

A priori: at NLO not well-defined:

can be absorbed by field-renormalization constants

$\rightarrow$ no need to renormalize mixing angles

Mixing angles

Transformation of bare interaction fields into bare mass eigenstates fields:

$c_x = \cos x, s_x = \sin x$

$$\begin{pmatrix} \varphi_{1,0} \\ \varphi_{2,0} \end{pmatrix} = \mathbf{R}_\varphi(\theta_0) \begin{pmatrix} \phi_{1,0} \\ \phi_{2,0} \end{pmatrix} = \begin{pmatrix} c_{\theta,0} & -s_{\theta,0} \\ s_{\theta,0} & c_{\theta,0} \end{pmatrix} \begin{pmatrix} \phi_{1,0} \\ \phi_{2,0} \end{pmatrix},$$

Renormalization of interaction fields and mixing angle θ:

$$\begin{pmatrix} \phi_{1,0} \\ \phi_{2,0} \end{pmatrix} = \begin{pmatrix} 1 + \frac{1}{2}\delta Z_{\phi_1\phi_1} & \frac{1}{2}\delta Z_{\phi_1\phi_2} \\ \frac{1}{2}\delta Z_{\phi_2\phi_1} & 1 + \frac{1}{2}\delta Z_{\phi_2\phi_2} \end{pmatrix} \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix}, \qquad \theta_0 = \theta + \delta\theta.$$

Field renormalization of bare mass eigenstate fields:

$$\begin{pmatrix} \varphi_{1,0} \\ \varphi_{2,0} \end{pmatrix} = \left[\begin{pmatrix} c_\theta & -s_\theta \\ s_\theta & c_\theta \end{pmatrix} \begin{pmatrix} 1 + \frac{1}{2}\delta Z_{\phi_1\phi_1} & \frac{1}{2}\delta Z_{\phi_1\phi_2} \\ \frac{1}{2}\delta Z_{\phi_2\phi_1} & 1 + \frac{1}{2}\delta Z_{\phi_2\phi_2} \end{pmatrix} + \begin{pmatrix} -s_\theta & -c_\theta \\ c_\theta & -s_\theta \end{pmatrix} \delta\theta \right] \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix}$$

$$= \begin{pmatrix} c_\theta & -s_\theta \\ s_\theta & c_\theta \end{pmatrix} \begin{pmatrix} 1 + \frac{1}{2}\delta Z_{\phi_1\phi_1} & \frac{1}{2}(\delta Z_{\phi_1\phi_2} - 2\delta\theta) \\ \frac{1}{2}(\delta Z_{\phi_2\phi_1} + 2\delta\theta) & 1 + \frac{1}{2}\delta Z_{\phi_2\phi_2} \end{pmatrix} \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix}.$$

Mixing angles

$\rightarrow$ no need to renormalize mixing angles

- Particularly useful if "too few" original/fundamental parameters
  e.g. mixing angle for CP-even Higgs bosons in the MSSM
- More cumbersome if mixing angle also appears as parameter
  e.g. mixing angle β for CP-odd/ charged Higgs states and $\tan\beta = \frac{v_2}{v_1}$

  $\uparrow$ no need for renormalization

  $\uparrow$ need to be renormalized

  careful bookkeeping needed

  v_i = Higgs vacuum expectation value i
- Additional original parameters $\lambda_i \xrightarrow{\text{replace}}$ mixing angles θ_i
  $\Rightarrow$ mixing angle θ_i fixed via the relation between λ_i and θ_i

  $\uparrow$ need to be renormalized

  (again bookkeeping)

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Gauge (in)dependence

In particular for mixing angles and $\tan\beta = \frac{v_2}{v_1}$:

Renormalization conditions leading to gauge dependences exit

$\Rightarrow$ for meaningful comparison: need to use always the same gauge

Wish:

"simple", process-independent, numerical well-behaved definition

Suggestions for $\tan\beta$ in the MSSM:

- Use original parameter instead $\rightarrow$ numerically unstable
- Use vanishing bare tadpoles

Tadpole renormalization

Two variants:

a) Vanishing renormalized tadpoles: $t_{S,0} = \overbrace{t_S}^{=0} + \delta t_S$

Condition: $\delta t_S + (\text{explicit tadpole loops}) = 0$
Advantage: No explicit tadpole diagrams need to be included
Disadvantage: $t_{S,0} = \delta t_S$ enters in relations between bare input parameters
$\rightarrow$ potentially gauge-dependent terms enter relations between renormalized parameters and observables

b) Vanishing bare tadpoles: $t_{S,0} = 0$ [Fleischer, Jegerlehner 80; Actis, Ferroglia, Passera, Passarino hep-ph/0612122]

Now: Explicit tadpole diagrams have to be taken into account
Advantage: No gauge-dependent δt_S enters in relations between bare input parameters
$\rightarrow$ relation between renormalized parameters and observables are gauge independent

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$\rightarrow$ large scale dependence

[Freitas, Stöckinger, hep-ph/0205281]

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Suggestions for $\tan\beta$ in the MSSM:

- Use original parameter instead $\rightarrow$ numerically unstable
- Use vanishing bare tadpoles and a $\overline{\text{DR}}$ scheme

  $\rightarrow$ large scale dependence
- Use one further Higgs mass $\rightarrow$ numerically unstable
- Use $A^0 \rightarrow \tau\tau$ to fix $\tan\beta \rightarrow$ process dependent

[Freitas, Stöckinger, hep-ph/0205281; Baro, Boudjema, Semenov, 0807.4668]

Gauge-independent mixing angles/parameters

Suggestions:

- Use pole structure: [Baro, Boudjema, 0906.1665]

  For MSSM sfermions:

$$\delta m_{\tilde{f}_{12}} = -\frac{1}{2} \lim_{m_{\tilde{f}_1} \to m_{\tilde{f}_2}} \left[\mathrm{Re}\Sigma_{\tilde{f}_1\tilde{f}_2}(m^2_{\tilde{f}_1}) + \mathrm{Re}\Sigma_{\tilde{f}_1\tilde{f}_2}(m^2_{\tilde{f}_2}) \right] = \mathrm{Re}\Sigma_{\tilde{f}_1\tilde{f}_2}\left(\frac{1}{2}(m^2_{\tilde{f}_1} + m^2_{\tilde{f}_2}) \right)$$

  Similar for Singlet Higgs extension (SSM) [Bojarski, Chalons, Lopez-Val, Robens, 1511.08120]

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- Use pinch technique and vanishing bare tadpoles in the 2HDM:

  e.g. $(m_H^2 - m_h^2)\delta\alpha = \mathrm{Re}\Sigma^{\mathrm{tad}}_{hH}\left(\frac{1}{2}(m_h^2 + m_H^2) \right)$ [Krause, Lorenz, Mühlleitner, Santos, Ziesche, 1605.04853, Kanemura, Kikuchi, Sakurai, Yagyu, 1705.05399]

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- $\overline{\mathrm{MS}}$ scheme and vanishing bare tadpoles (2HDM/SSM)

  [Denner, Jenniches, Lang, Sturm,1607.07352; Altenkamp, Dittmaier, H.R., 1704.02645; Denner, Lang, Uccirati, 1705.06053; Altenkamp, Boggia, Dittmaier, 1801.07291]

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- Use fundamental parameter instead (SSM/2HDM) [Bojarski, Chalons, Lopez-Val, Robens, 1511.08120; Altenkamp, Dittmaier, H.R., 1704.02645]

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- Use fundamental parameter instead (SSM/2HDM) [Bojarski, Chalons, Lopez-Val, Robens, 1511.08120; Altenkamp, Dittmaier, H.R., 1704.02645]

- Use process to fix the mixing angle [Bojarski, Chalons, Lopez-Val, Robens, 1511.08120; Krause, Lorenz, Mühlleitner, Santos, Ziesche, 1605.04853]

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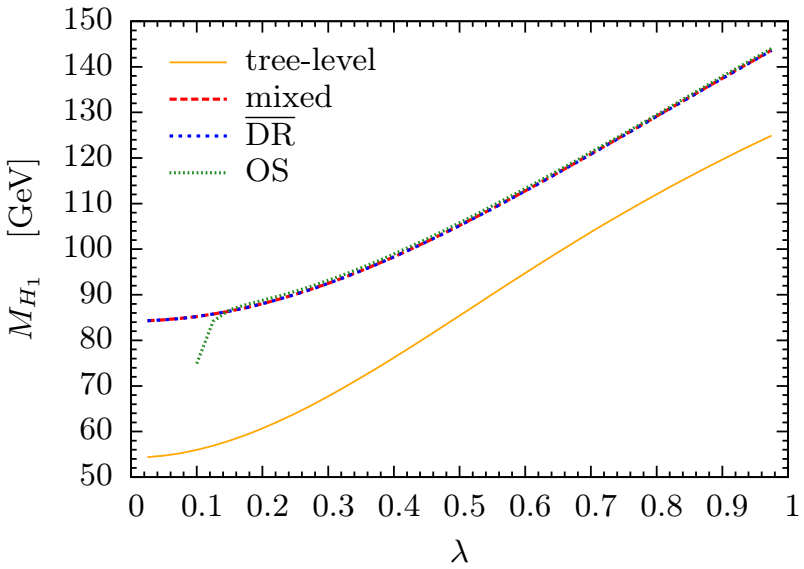
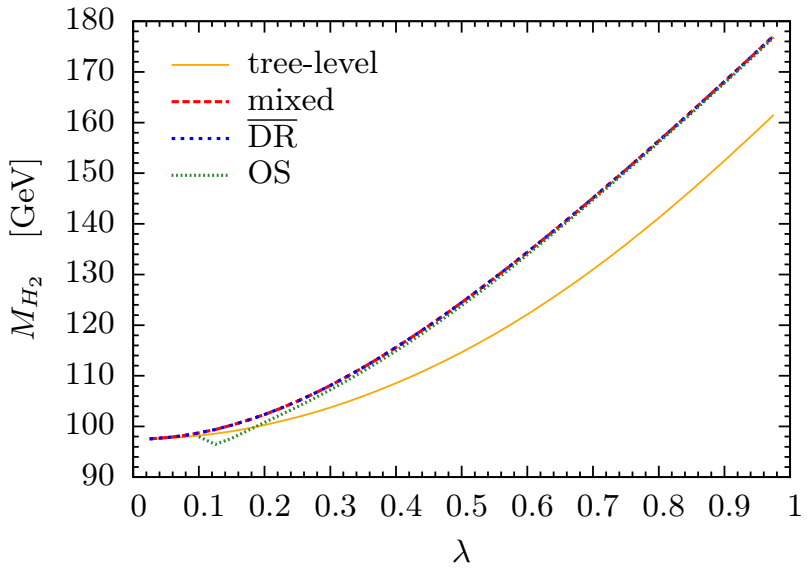
Example: Higgs masses in the CP-conserving NMSSM

Different renormalization schemes: [Ender, Graf, Mühlleitner, H.R., 1111.4952]





- in general good agreement between the different schemes ($\lesssim 1$ GeV)
- for small λ: OS-scheme deviates due to finite $\frac{1}{\lambda}$ terms in the counterterms

$\kappa = \lambda/5$, $\tan\beta = 2$, $A_\lambda = 500$ GeV, $A_\kappa = -10$ GeV, $v_S = \frac{1}{\sqrt{2}}\frac{250}{\lambda}$ GeV,
$M_S = 300$ GeV, $A_t = A_b = A_\tau = -1.5 M_S$, $M_1 = M_S/3$, $M_2 = 2/3 M_S$, $M_3 = 2 M_S$

Example: 2HDM: Four possibilities for λ_3/α and β

- Scheme $\lambda_{3_{\overline{\text{MS}}}}$: see [Altenkamp, Dittmaier, HR 1704.02645]

  λ_3 $\overline{\text{MS}}$, $\tan\beta$ $\overline{\text{MS}}$
  tadpole scheme: $t_S = 0$

- Scheme $\alpha_{\overline{\text{MS}}}$:

  α instead of λ_3: α $\overline{\text{MS}}$, $\tan\beta$ $\overline{\text{MS}}$
  tadpole scheme: $t_S = 0$

- Scheme FJ:

  α $\overline{\text{MS}}$, $\tan\beta$ $\overline{\text{MS}}$
  tadpole scheme: $t_{S,0} = 0$

  see also [Krause, Mühlleitner, Lorenz, Santos, Ziesche 1605.04853; Denner, Jenniches, Lang, Sturm 1607.07352]

- Scheme FJ λ_3:

  λ_3 $\overline{\text{MS}}$, $\tan\beta$ $\overline{\text{MS}}$
  tadpole scheme: $t_{S,0} = 0$

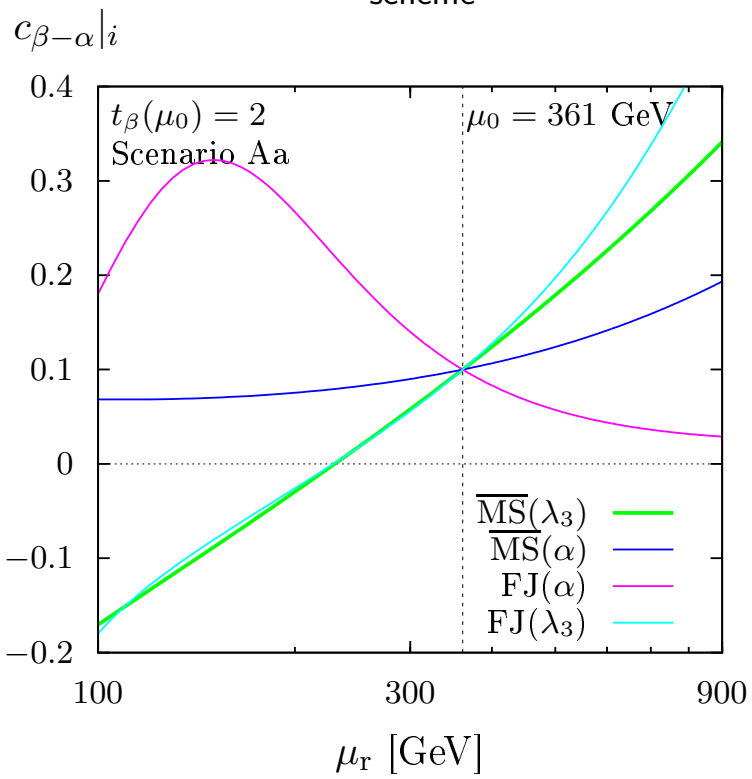
Running of $\cos(\beta - \alpha)$ in different schemes

[Altenkamp, Dittmaier, HR 1704.02645, 1710.07598]

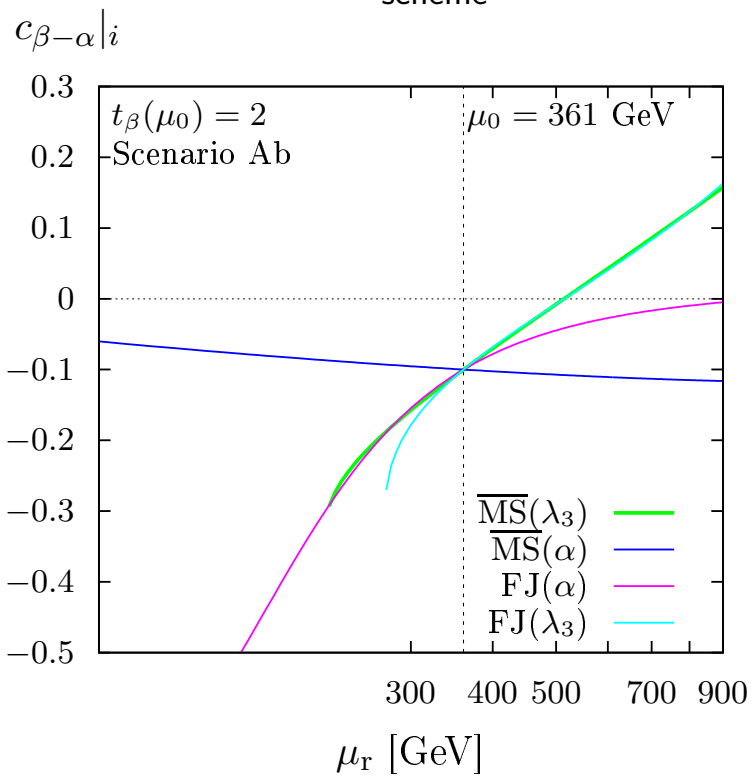
Scenario A: $M_h = 125$ GeV, $M_H = 300$ GeV, $M_{A_0} = M_{H^+} = 460$ GeV, $\lambda_5 = -1.9$, $\tan\beta = 2$

$\mu_0 = M_h + M_H + M_A + 2M_{H^+}$ for 2HDM type 1, see [Haber , Stål, 1507.04281]

Aa: $\cos(\beta - \alpha)|_{\substack{\text{input}\\ \text{scheme}}}(\mu_0) = 0.1$:



Ab: $\cos(\beta - \alpha)|_{\substack{\text{input}\\ \text{scheme}}}(\mu_0) = -0.1$:

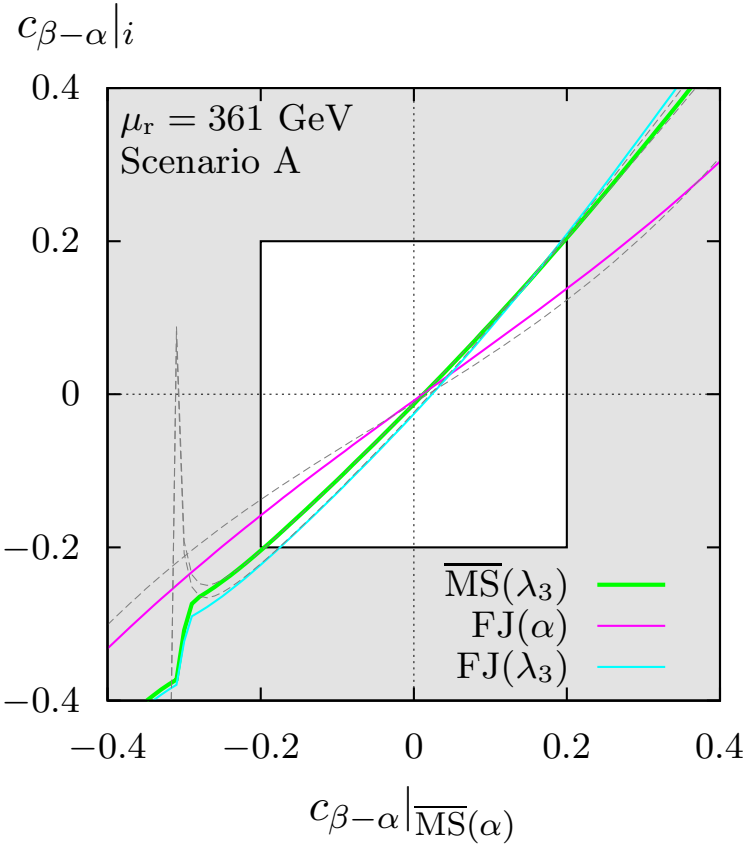


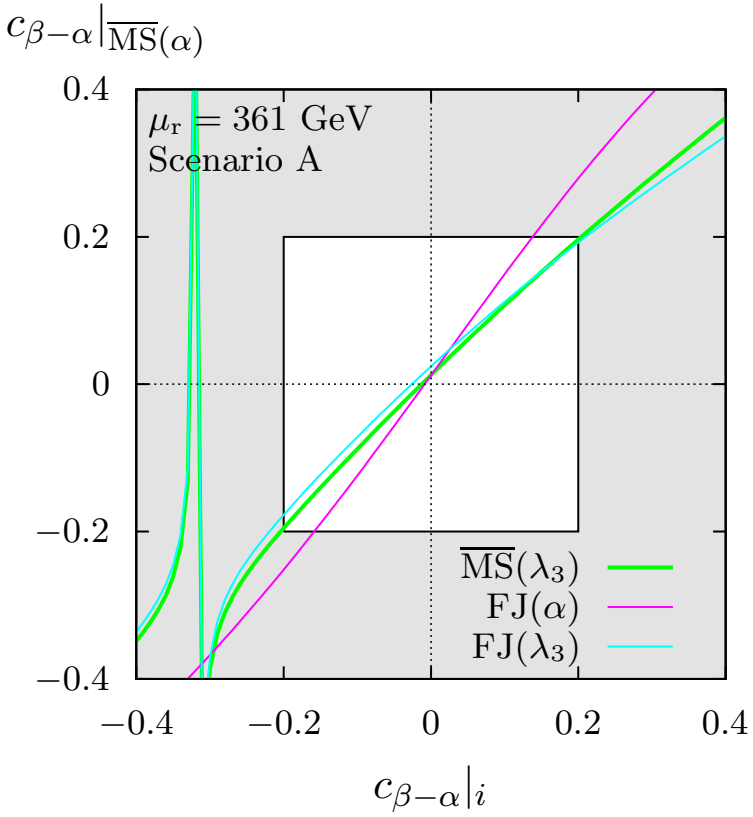
$\Rightarrow$ sizeable running effects

Conversion of parameters

[Altenkamp, Dittmaier, HR 1704.02645, 1710.07598]

Conversion: $p_{\mathrm{RS2}} = p_{\mathrm{RS1}} + \delta p_{\mathrm{RS1}}(p_{\mathrm{RS1}}) - \delta p_{\mathrm{RS2}}(p_{\mathrm{RS2}})$





- Scenarios depend on the chosen renormalization scheme.

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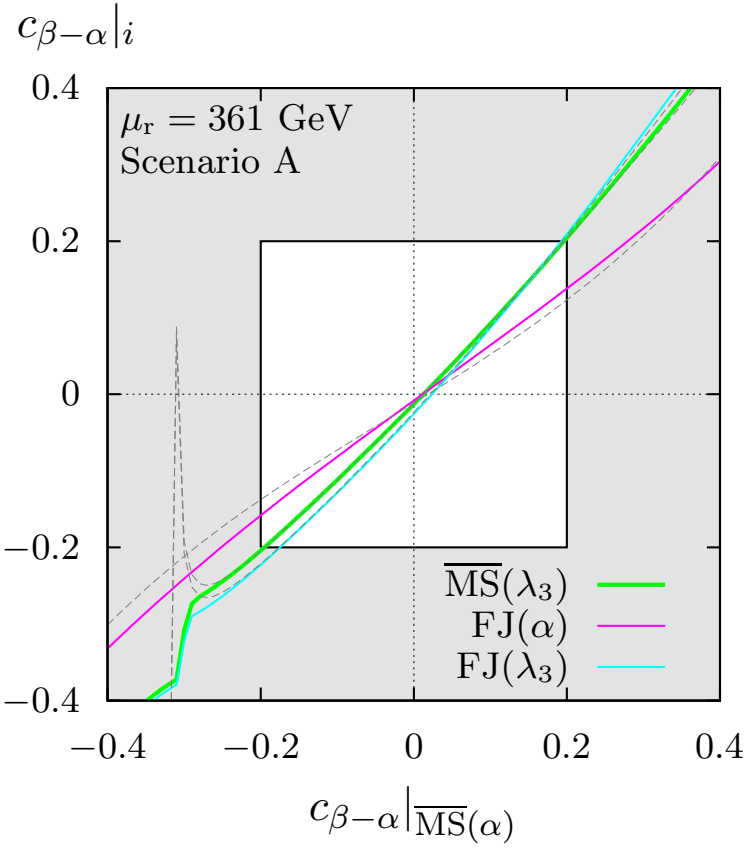
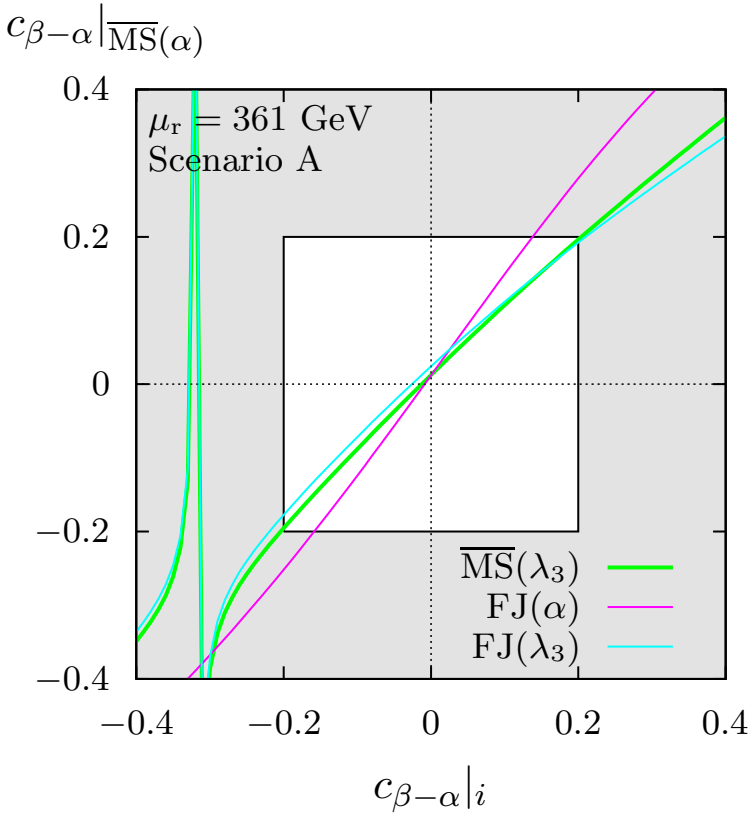
Conversion: $p_{\mathrm{RS2}} = p_{\mathrm{RS1}} + \delta p_{\mathrm{RS1}}(p_{\mathrm{RS1}}) - \delta p_{\mathrm{RS2}}(p_{\mathrm{RS2}})$

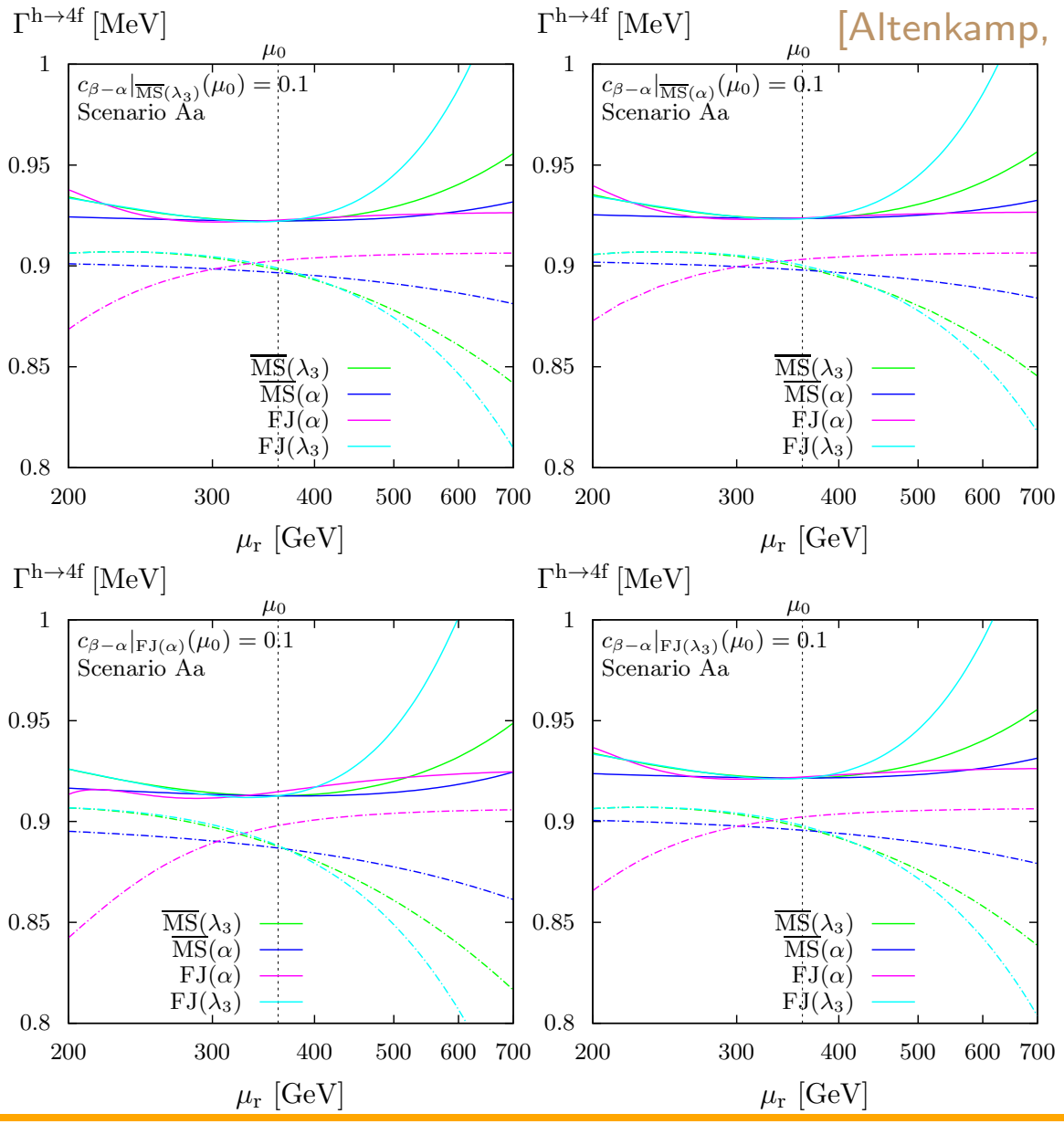




- Peak region: λ_3 is a bad input parameter if $\cos(2\alpha) \approx 0$,
  (to avoid the issue: choose different λ_i).

μ_r dependence of $\Gamma(h \to 4f)$

[Altenkamp, Dittmaier, HR 1710.07598]

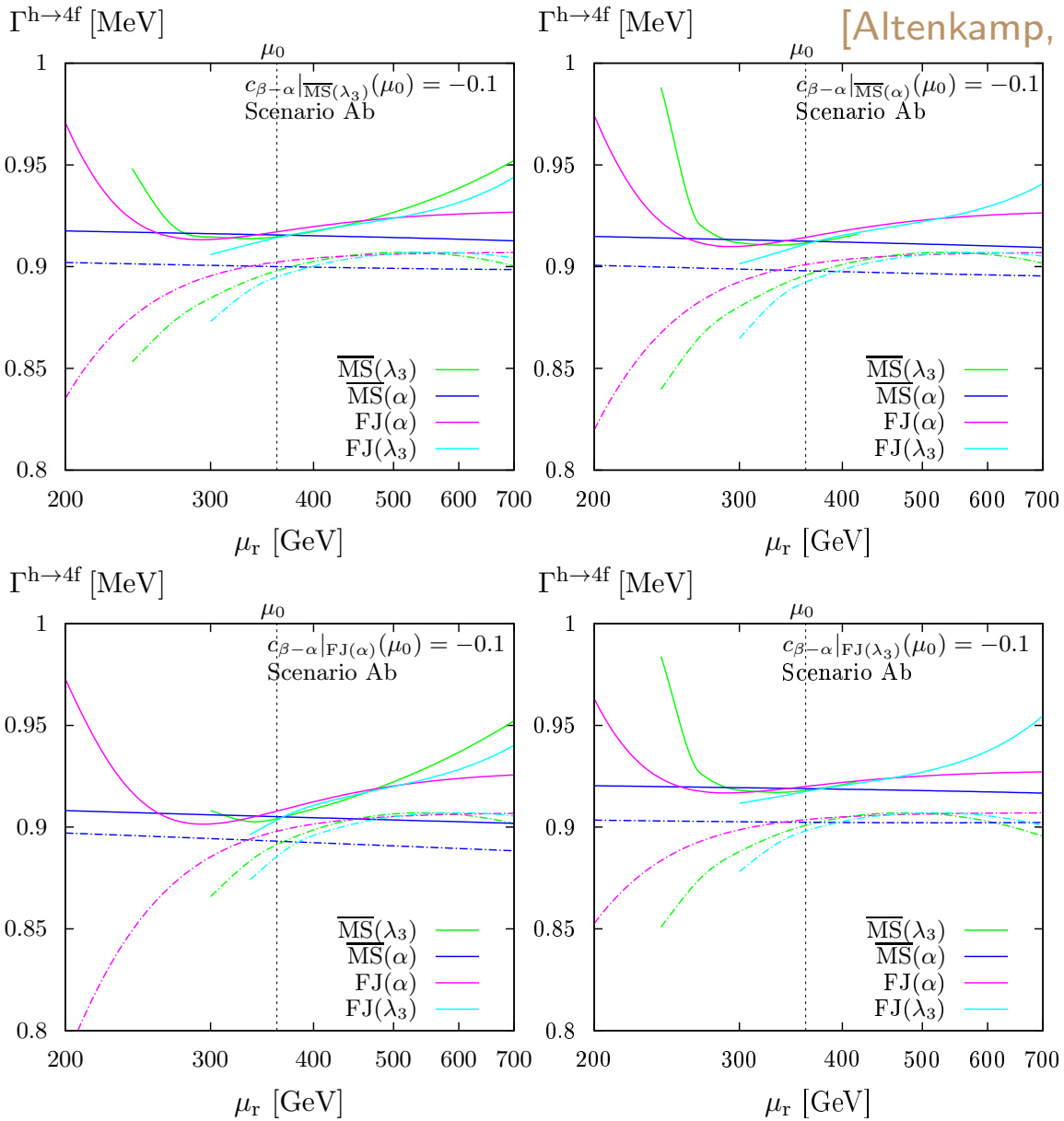


For all input schemes:

- Clear plateau
- Reduction of scale dependence from LO to NLO

μ_r dependence of $\Gamma(h \to 4f)$

[Altenkamp, Dittmaier, HR 1710.07598]



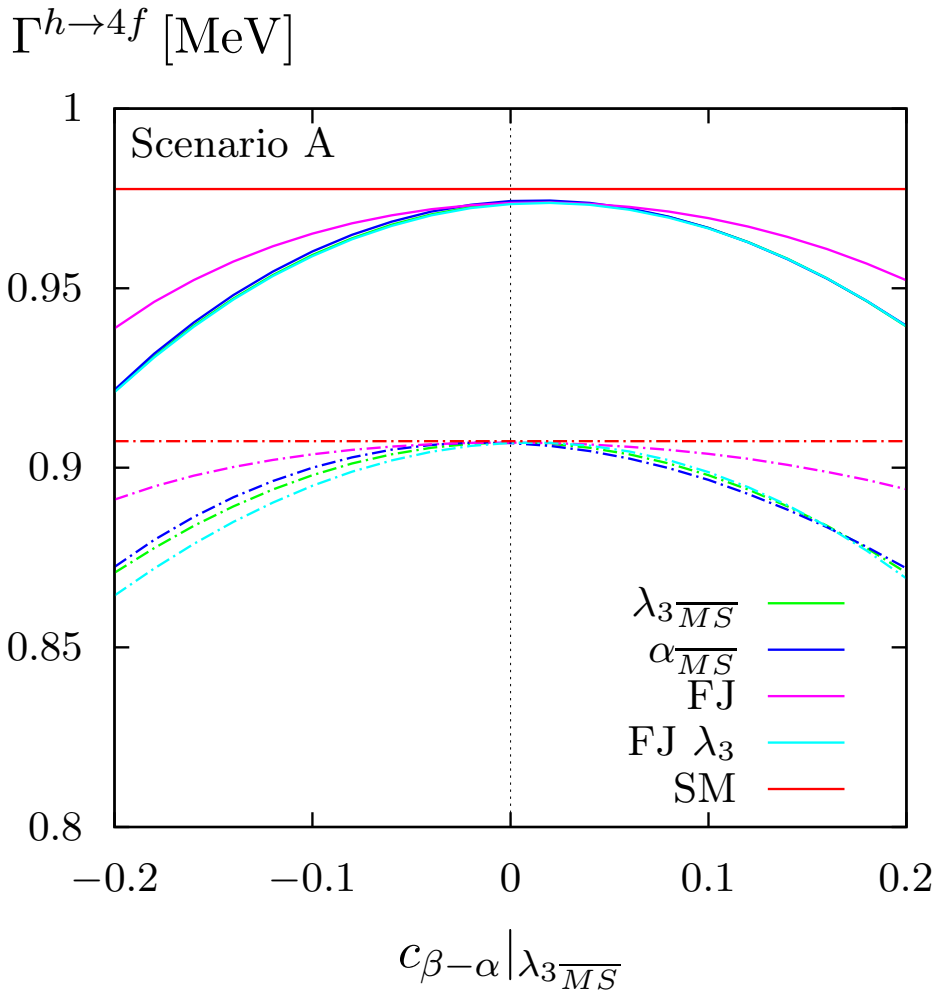
Now scenario Ab:

For all input schemes:

- Plateau
- Reduction of scale dependence from LO to NLO

$\cos(\beta - \alpha)$ dependence of $\Gamma(h \to 4f)$

[Altenkamp, Dittmaier, HR 1704.02645, 1710.07598]



$\mu_0 = (M_h + M_H + M_{A_0} + 2M_{H^+})/5$

LO: dashed

NLO: solid

- Scheme λ_3 $\overline{\text{MS}}$ used:

$\Gamma^{h\to 4f}_{\text{2HDM, LO}}|_{\lambda_3,\overline{\text{MS}}} = s^2_{\beta-\alpha}\Gamma^{h\to 4f}_{\text{SM, LO}}$

Conclusion

- Symmetry relations need to be respected:

  Possible issue: On-shell particles $\leftrightarrow$ mixing of higher orders

- Additional parameters:

  Reasonable definitions?

- Gauge independence:

  Recently a lot of discussion about mixing angles/parameters

- Numerical stability:

  - $\star$ Not all theoretical reasonable schemes lead to numerically well-behaved predictions
  - $\star$ Compare different renormalization schemes (do not forget parameter conversion)

MASS2018

MASS 2018

Origin of Mass at the High Energy and Intensity Frontier

May 28 - Jun 1, 2018

Invited Plenary Speakers

Brian Batell (U. Pittsburgh)
Niklaus Berger (PRISMA, U. Mainz)
Giacomo Cacciapaglia (U. Lyon, CNRS/IN2P3)
Albert De Roeck (CERN, U. Antwerp)
Francesca Di Lodovico (Queen Mary, U. London)
Ulrik Egede (Imperial College London)
Simon Eidelman (Novosibirsk State U.)
Stefano Forte (U. Milan)
Rohini Godbole (IISc, Bangalore)
Frederick Gray (Regis U.)
Benjamin Grinstein (U. California, San Diego)
Howard Haber (U. California, Santa Cruz)
Per Johansson (U. Sheffield)
Jacobo Lopez Pavon (CERN)
Joachim Mnich (DESY, Hamburg)
Angela Papa (PSI)
Paride Paradisi (U. Padua, INFN)
Antonio Pich (Valencia U., IFIC)
Chengping Shen (Beihang U., Beijing)
Ana M. Teixeira (Clermont, CNRS)
Ruth Van de Water (Fermilab)

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Local Organization

F. Sannino, M. T. Frandsen, H. Rzehak, C. Hagedorn

Administrative Support

E. Mølgaard, L. Ch. Nielsen

Conference venue

University of Southern Denmark
Campus Odense
Auditorium O100 & adjacent rooms

Deadline for registration

May 7, 2018

Webpage

cp3-origins.dk/mass2018

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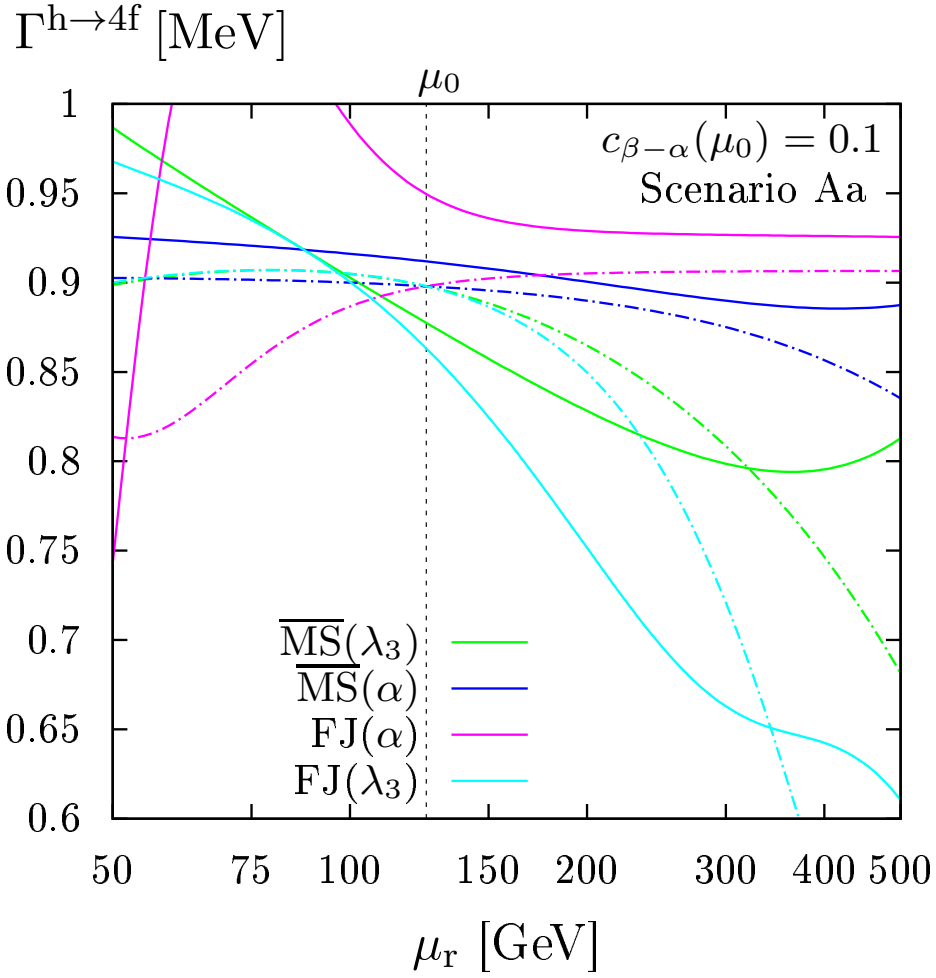
μ_r dependence of $\Gamma(h \to 4f)$

[Altenkamp, Dittmaier, HR 1704.02645]

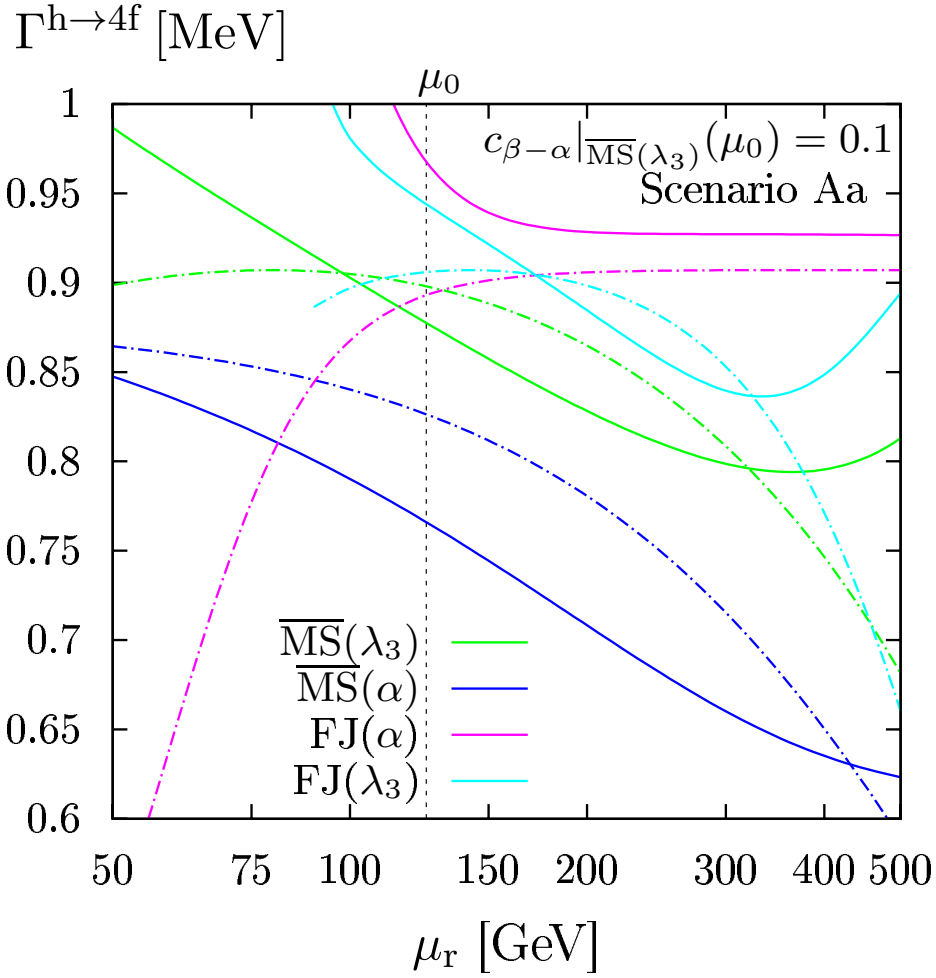


"naive" scale: $\mu_0 = M_h$

LO: dashed
NLO EW: solid

- No conversion:
  scenario interpreted as given in respective scheme
- No clear plateau around $\mu_r = \mu_0$ at NLO

μ_r dependence of $\Gamma(h \to 4f)$



[Altenkamp, Dittmaier, HR 1704.02645]

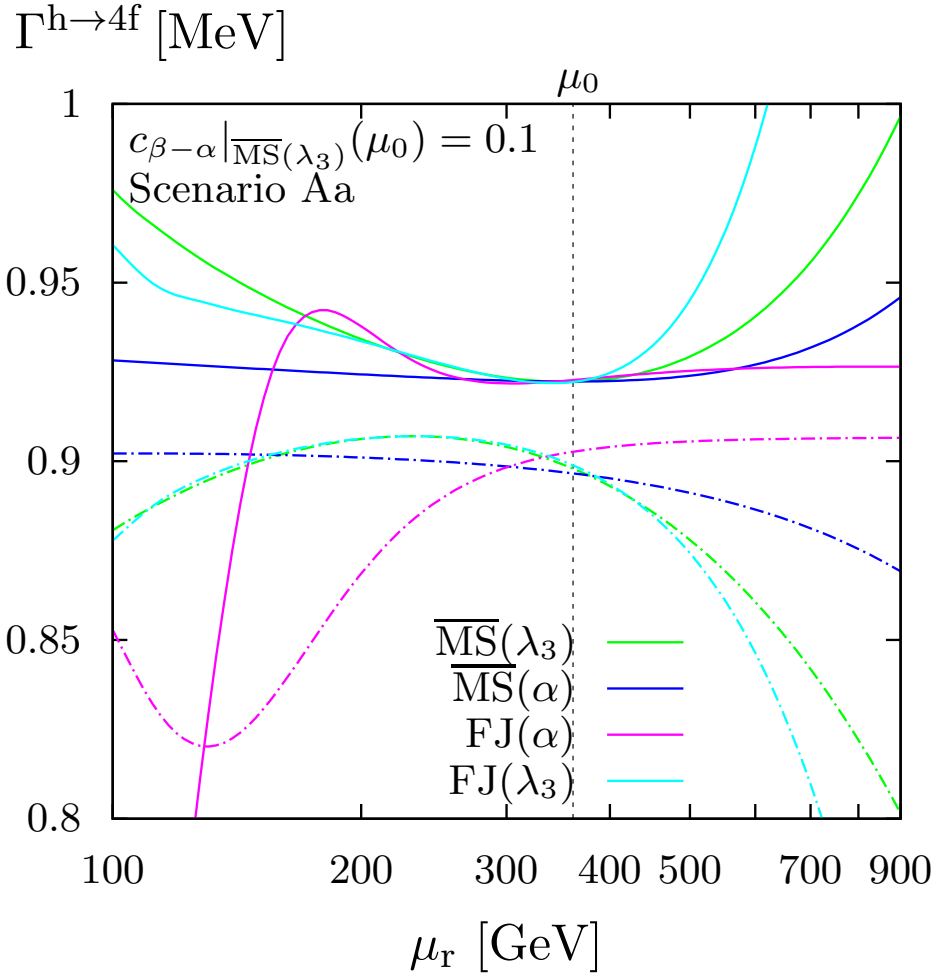
"naive" scale: $\mu_0 = M_h$

LO: dashed
NLO EW: solid

- Scheme λ_3 $\overline{\rm MS}$ used
- With conversion:
  Sizeable effects already at LO
- No clear plateau around
  $\mu_r = \mu_0$ at NLO

μ_r dependence of $\Gamma(h \to 4f)$

[Altenkamp, Dittmaier, HR 1704.02645]



$\mu_0 = (M_h + M_H + M_{A_0} + 2M_{H^+})/5$

LO: dashed
NLO EW: solid

- Scheme λ_3 $\overline{\rm MS}$ used
- Clear plateau around $\mu_r = \mu_0$ at NLO
- Scale dependence reduced from LO to NLO